Atmosphere-Ocean Interaction of the MJO from Unmanned Airborne Vehicles

A component of Coupled Air-Wave-Sea Processes in the Subtropics Departmental Research Initiative

Christopher J. Zappa
Lamont-Doherty Earth Observatory of Columbia University
Ocean and Climate Physics Division
61 Route 9W, Palisades, NY 10964

Phone: (845) 365-8547 Fax: (845) 365-8157 email: zappa@ldeo.columbia.edu

Arnold L. Gordon
Lamont-Doherty Earth Observatory of Columbia University
Ocean and Climate Physics Division
61 Route 9W, Palisades, NY 10964

Phone: (845) 365-8325 Fax: (845) 365-8157 email: agordon@ldeo.columbia.edu

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LONG-TERM GOALS

We are part of a multi-institutional research team funded by the ONR-sponsored the ***Coupled Air-Wave-Sea Processes in the Subtropics Departmental Research Initiative***. The primary research goals of the program include: (i) Surface flux observations in regions of known coupled modes, (ii) Co-located observations of atmospheric and oceanic vertical structure and evolution, and (iii) Ocean mixed layer and marine atmospheric boundary layer dynamics, and interactions between these and the surface wave field, the free atmosphere, and the interior ocean. Our goals are to contribute innovative measurements, analyses and models of the sea surface temperature at length scales as small as a 1 meter up to 100's of kilometers. This characterization includes the skin SST, waves, wave breaking, and upper ocean processes.

OBJECTIVES

The Madden-Julian Oscillation (MJO) is an intraseasonal oscillation which is most closely identified with the tropical Indian and Pacific Oceans, characterized by an eastward progression of a large (~2000 km) pattern, extending from the equator into the adjacent subtropical belts, with enhanced and suppressed rainfall. In the context of this DRI, understanding the complex processes involved in locations such as the MJO as it passes over the eastern Indian Ocean are necessary steps for evaluating the modulation of SST and atmosphere-ocean feedbacks, for validating ocean and climate models, and for making prognostic assessments of oceanic circulation.

Sea-air exchange displays a clear seasonal cycle, but there are also significant fluctuations at periods less than seasonal, the so-called intraseasonal oscillations. Notably is the Madden-Julian Oscillation

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(MJO), which is most closely identified with the tropical Indian and Pacific Oceans, though there is a weaker tropical Atlantic presence. The MJO is characterized by an eastward progression of a large (~2000 km) pattern, extending from the equator into the adjacent subtropical belts, with enhanced and suppressed rainfall. The wet phase marked by enhanced convection and precipitation is followed by a dry phase where convection is suppressed. The anomalous rainfall pattern is usually first evident over the western Indian Ocean, from where it propagates eastward at 5 to 10 m/s over the warm waters of the eastern Indian and western to central tropical Pacific. The pattern becomes less evident as it moves over the cooler ocean waters of the eastern Pacific but often reappears over the tropical Atlantic Ocean and may come full circle as it reaches the western and Indian Ocean. Each cycle lasts approximately 30–60 days, though fluctuations at less than 30 days are also present. Interannual variability in the strength of MJO is related to the phase of ENSO: weaker in El Niño; stronger during La Niña. MJO events may contribute to the speed of development and intensity of El Niño and La Niña episodes. For further information of MJO, see: http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/mjo.shtml.

As suggested, the MJO is thermodynamically coupled to the upper layer of the tropical Indian Ocean in both its wet and dry phases that are indicated by outgoing long wave radiation (OLR) anomalies. The MJO induced wind, surface shortwave and latent heat fluxes exert control on the ocean mixed layer. The total wind speed largely is thought to control the latent heat flux, thus modulating the warming anomaly to the ocean. OLR is reduced (Negative OLR anomalies) during the wet MJO phase, a product of deep 'cold top' clouds, enhanced precipitation, a reduction in insolation, with cooling of the ocean and negative sea surface temperature (SST) anomaly. Positive OLR anomalies (dry MJO phase) increase the downward surface shortwave flux, as well as a reduction in the upward latent heat flux due to smaller wind speeds leading to a positive SST anomaly. SST being an accumulative response to the surface flux modifications, typically lags by 1-2 weeks or ¼ of the MJO cycle to the wet/dry phases. Recent Argo measurements have shown that these surface driven MJO anomalies force eastward-propagating oceanic equatorial Kelvin waves that extend downward to 1500m [*Matthews et al.*, 2007].

A recent MJO workshop [*Sperber and Waliser*, 2008] has suggested that observations are lacking for many important processes (e.g. convective momentum transport, moistening of the boundary layer, diurnal cycle of shallow convection, and surface fluxes). It also suggests the measurements are needed to provide insight into a variety of MJO characteristics including the transition to and from the convective phase including scale interactions with mesoscale systems, and the diurnal cycle over the land and ocean. The workshop highlighted that a better understanding of the vertical structure of the atmosphere, including clouds, moisture cycling, and related properties (e.g., long wave and shortwave radiation, humidity), is not adequately represented in simulations of the MJO.

The broad science questions to be addressed by our program include the following:

- How do atmospheric boundary layer processes and sea-air coupling over the eastern Indian Ocean modulate the intensity and spatial extent of MJO and of higher frequency fluctuations?
- What regulates the sea-wave-air interactions and the response of the mixed layer during periods of MJO forcing?
- How do the water column profile characteristics evolve over the course of an MJO cycle and at higher frequency fluctuations?

Understanding the complex processes involved in locations such as the MJO as it passes over the eastern Indian Ocean are necessary steps for evaluating the modulation of SST and atmosphere-ocean

feedbacks, for validating ocean and climate models, and for making prognostic assessments of oceanic circulation. Our science goals are directly related to the special focus areas of the DRI described above in Long-Term Goals.

Our science goals complement and parallel those of J. Moum of Oregon State. They plan to deploy a fully instrumented Chameleon turbulence profiler along with a bow-mounted CT chain to understand the upper ocean processes important to the MJO cycle from the R/V Revelle. Our science goals also complement and parallel those of J. Edson of the University of Connecticut who plans to make direct measurements of latent heat flux on the R/V Revelle, as well as more conventional rawinsonde launches in addition to turbulent air-sea fluxes from the ship during the IOP. Further, we expect to have interactions with the project led by R. Pinkel and J. Smith of Scripps that is performing measurements of the diurnal warm layer using the WireWalker Array.

APPROACH

As our Annual Report title suggests, we had planned to use UAVs as our observing platform to be deployed from the R/V Revelle. UAVs give the distinct advantage over conventional manned aircraft due to the considerably more affordable cost and due to the ability to fly constantly at roughly 20 hours a day for 30 days. This amounts to a duty cycle of nearly 85%. Furthermore, the ability to launch and recover from the UNOLS vessel significantly increases flexibility for the sampling strategy as there is less transit time to the site by a conventional manned aircraft from land. We planned to examine the temporal and spatial scales of the processes manifested as ABL structure of wind, humidity, temperature, pressure, and SST. We also planned to instrument the UAV with a point radiometric SST measurement along with net solar and longwave. Other capabilities (not all simultaneously) were to be a laser altimeter for surface waves, high-resolution IR imaging for SST variability, video imaging, and dropsondes. During the course of this planning phase of the DRI, the logistical hurdles were determined to be substantial and the observing platform for our measurement module was moved to manned aircraft.

An aircraft platform will be used for in-situ and remote sensing observations of the atmosphere, augmented by high-resolution infrared imaging of the ocean surface temperature to simultaneously identify the mechanisms responsible for the upper-ocean response and water mass modification within the MJO region.

The aircraft platform intensive observing period (IOP) will quantify the surface energy budget components over the ocean, describe the forcing for and near surface properties of regional meso-scale atmospheric flows responsible for MJO formation, and document the oceanic response to these flows at high vertical and temporal resolution. The measurements will be the first such coordinated atmospheric and oceanic measurements to be made in the MJO environment and therefore provide an unprecedented view of the coupled atmospheric and oceanic processes over an MJO cycle of 30-60 days.

Combining airborne remote sensing and in-situ observation in the eastern Indian Ocean is a very effective approach. Airborne observations allow for the measurement of ocean-atmosphere fluxes of heat and momentum as well as the spatial and temporal variability of atmospheric boundary layer (ABL), surface waves and SST within and external to the affected MJO region. These measurements greatly enhance our understanding of the ocean processes associated with the MJO including its

feedbacks on the atmospheric boundary layer convective structure and maintenance, as well as on the overall quantitative role of MJO in tropical and subtropical coupled ocean-atmosphere processes.

Naturally the experiment design of our data collection plan will be developed in collaboration with the other components of the Coupled Air-Wave-Sea Processes in the Subtropics Departmental Research Initiative. What follows are preliminary considerations of the experimental design. The lateral scale of a typical MJO is 2000 km, half being a wet phase [negative OLR], the other half being the dry phase [positive OLR]. The amplitude of a secession of MJO events varies; during an El Niño [La Niña] MJO events are particularly weak [strong]. As we can't be sure what MJO or ENSO phase will be encountered during the UNOLS occupation of the region in the eastern tropical Indian Ocean the following plan is generic.

Manned aircraft give the distinct advantage over conventional shipboard measurements due to the ability to fly great distances and provide exceptional spatial coverage using roughly 150 hours over 30 days. Furthermore, the ability to cover such great distance significantly increases flexibility for the sampling strategy than allowed by a research vessel. Consistent with the capabilities of the manned aircraft a possible scenario may be as follows: The manned aircraft can be flown in a 'stack-mode' or along horizontal path cutting across the MJO patterns. At this point one may assume a series of flights within the dry MJO phase (positive OLR anomaly) and wet MJO phase (negative OLR anomaly) within the atmosphere boundary layer, assumed to be ~2 km to within 100 m of the sea surface.

A mix of stack-mode and horizontal path mode will be run over a 2 day period along a specific latitude (likely between the equator and 8°S). This will be done as frequently during the UNOLS vessel presence as flight time allows, producing a sequence of 'snap-shots' of to investigate the evolution of the MJO ABL structure and sea surface conditions. In addition, meridional lines and stack-mode, will be run over the DYNAMO moorings (0°S 77°E, 1.7°S 76.8°E, and 8°S 77°E).

Our capabilities contribute a comprehensive measurement effort to this DRI to determine the atmospheric and oceanic properties of the MJO. Our effort is designed to interface synergistically with complementary ocean and atmospheric investigations in this DRI. Our vision is to incorporate our atmospheric observational module using an unmanned airborne vehicle (UAV) within the DRI field programs to provide optimal sampling of fundamental atmospheric processes associated with the MJO as well as a shipboard deployment of drifting buoy sensors to simultaneously identify the mechanisms responsible for the upper-ocean response and water mass modification within the MJO region. The unmanned aircraft platform intensive observing period will quantify the surface energy budget components over the ocean, describe the forcing for and near surface properties of regional mesoscale atmospheric flows responsible for MJO formation, and document the oceanic response to these flows at high vertical and temporal resolution. The measurements will be the first such coordinated atmospheric and oceanic measurements to be made in the MJO environment and therefore provide an unprecedented view of the coupled atmospheric and oceanic processes over an MJO cycle of 30-60 days.

We build substantially on our accumulated expertise in sea surface processes and air-sea interaction. We are working within the larger team measuring and characterizing the ocean surface properties, namely SST. Airborne IR imagery will provide high spatial resolution calibrated SST variability. The image scale will be roughly 500 m to 1000 m (depending on altitude) with resolution of order 1 m. This team is contributing the following components to the primary sea surface imagery data gathering effort in DYNAMO:

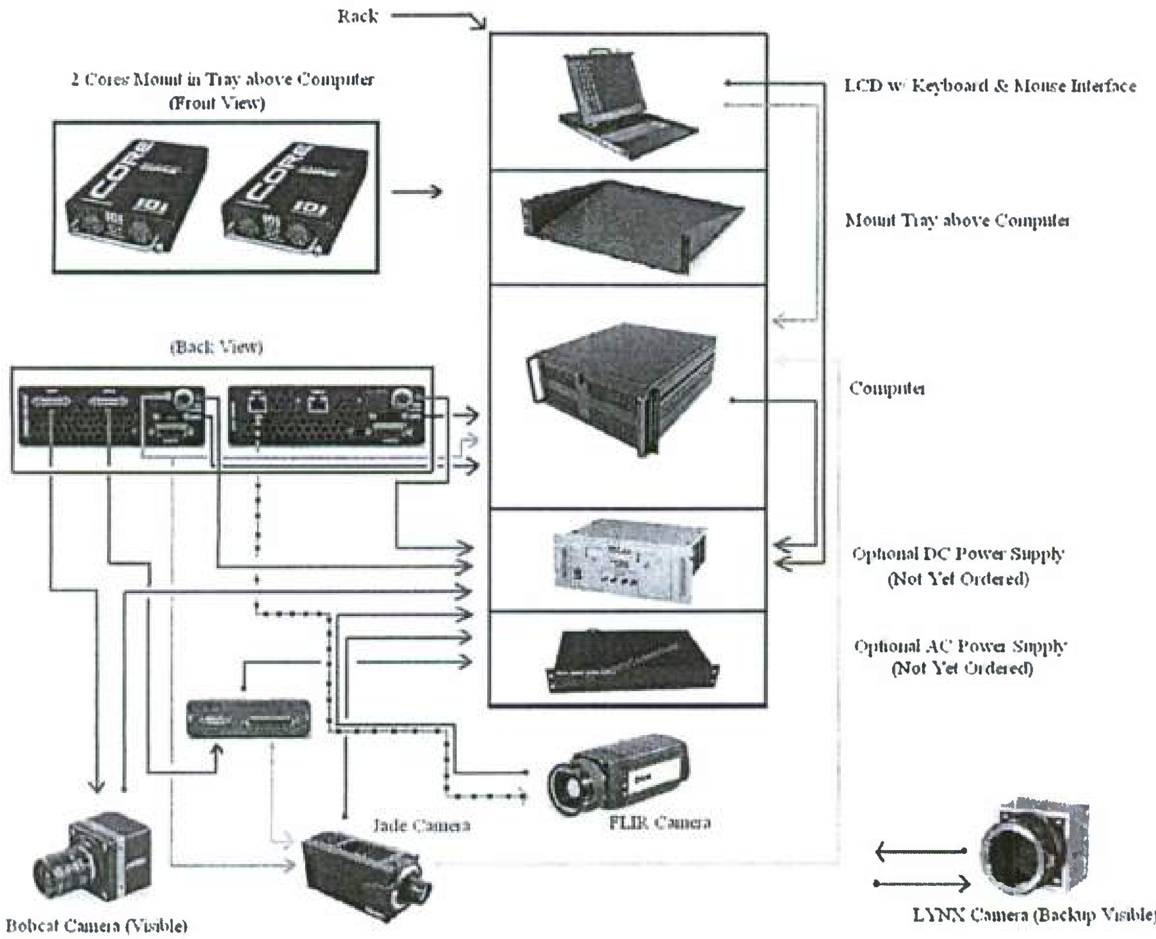
- fast response, infrared (IR) imagery to characterize SST signatures including upper-ocean convection, freshwater lenses due to rain, Langmuir circulation, internal waves, ramping of near-surface stratification, etc. at scales of O(1m-1000m)
- high resolution video imagery to record general ocean surface conditions and whitecap data using wide field-of-view to quantify scales of O(1m-1000m)

The IR and Visible imaging provide an important characterization of the wind-wave field since they are used to characterize the kinematics of wave breaking (white capping only). Analyses of the airborne IR and Visible imageries will benefit significant from over-flight over the Ship and/or mooring array for better understanding of the wave effects on the upper ocean turbulence and stratification structure and the wave effects on the air-sea fluxes. These measurements will elucidate a variety of mechanisms related to atmospheric and sub-surface phenomena that produce horizontal variability in SST over a wide range of scales under MJO forcing. This study will investigate the mesoscale, sub-mesoscale, and small-scale variability.

We will be flying on the NOAA P3 aircraft and work with Djamal Khelif of UC Irvine and Qing Wang of the Naval Postgraduate School to instrument the manned aircraft. The suite of instruments aboard the NOAA P3 will allow us to characterize the surface and atmospheric state, measure net radiative fluxes, and estimate the heat, moisture, and momentum fluxes. These data will be used to relate the basic state variables of the atmosphere to remotely-sensed characteristics of the waves and SST_{skin} at the air-sea interface. The main goal of flights with this instrument suite will be to characterize the properties of the surface associated with time varying atmospheric conditions of the MJO, including SST_{skin}, as well as wave height and fine-scale surface height variation and roughness from laser profiles. A second goal of the manned aircraft P3 mapping is to provide surface information at higher spatial resolution and with better temporal sampling than is available from the satellite data.

WORK COMPLETED

Lamont-Doherty Earth Observatory of Columbia University (LDEO) developed an airborne imaging system that utilizes both infrared and visible cameras to map the ocean surface SST and ocean surface processes. With our added payload capacity on the NOAA P-3, thermal infrared (IR) imagery demonstrates the ocean surface processes that are relevant to atmosphere-ocean interaction. As the focus of the measurement module, we will implement a small sensitive uncooled IR camera to map the temperature structure of the ocean's surface. The FLIR SC655 is an un-cooled microbolometer focal plane array of 640 x 480 elements that are sensitive to 8.0-12.0 micron radiation. The microbolometer array performance will allow for the determination of temperature variability of less than 50 mK. Additionally, we will deploy a JADE LWIR 570 Sterling-cooled Mercury-Cadmium-Telluride (MCT) focal plane array of 320 x 240 elements that are sensitive to 8.0-9.3 micron radiation. The MCT focal plane array performance will allow for the determination of temperature variability of less than 20 mK. The combination of cameras will allow us to capture a multitude of scales from O(1m - 1000m). Finally, an Imperx model Bobcat 2520 visible camera with 2500 x 2000 elements was deployed for high-resolution determination of the ocean surface structure. Figure 1 shows the schematic drawing of the camera and image acquisition system mounted aboard the NOAA P-3 in preparation for the upcoming measurements in the Indian Ocean in support of DYNAMO.



Power (AC vs DC TBD)

Multi VGA/Keyb/Mouse

JADE RS-232

CAT5e or CAT6 (Long vs Short TBD)

LVDS (Long vs Short TBD)

BNC for TTL

CameraLink (Long vs Short TBD)

HBA-to-eSATA (4 Breakouts)

Figure 1. Schematic drawing of the instrument setup and image acquisition system installed on the NOAA P-3 for the LDEO airborne component in DYNAMO program from 3 November 2011 through 15 December 2011.

RESULTS

The measurement IOP for the P-3 is to take place from 3 November 2011 through 15 December 2011 based in Diego Garcia. As such, there are no results other than experiment meetings, instrument preparations and completed innovative systems discussed in the "Work Completed."

IMPACT/APPLICATIONS

Understanding the complex processes involved in locations such as the MJO as it passes over the eastern Indian Ocean are necessary steps for evaluating the modulation of SST and atmosphere-ocean feedbacks, for validating ocean and climate models, and for making prognostic assessments of oceanic circulation.

REFERENCES

Matthews, A. J., P. Singhruck, and K. J. Heywood (2007), Deep ocean impact of a Madden-Julian Oscillation observed by Argo Floats, *Science*, *318*, 1765-1769.

Sperber, K. R., and D. E. Waliser (2008), New approaches to understanding, simulating, and forecasting the Madden-Julian Oscillation, *Bulletin of the American Meteorological Society*, *DOI:10.1175/2008BAMS2700.1*, 1917-1920.

REPORT OF INVENTIONS AND SUBCONTRACTS

(Pursuant to "Patent Rights" Contract Clause) (See Instructions on back)

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1.a. NAME OF CONTRACTOR/SUBCONTRACTOR	c. CONTRACT NUMBER	2.a. NAME OF GOVERNMENT PRIME CONTRACTOR	c. CONTRACT NUMBER	3. TYPE OF REPORT (X one)
Columbia Univ Lamont-Doherty Earth Obser	N00014-10-1-0545	Columbia Univ Lamont-Doherty Earth Obse	N00014-10-1-0545	a. INTERIM [ ] b. FINAL [X]
b. ADDRESS (Include ZIP Code)	**d. AWARD DATE** (YYYYMMDD)	**b. ADDRESS** (Include ZIP Code)	**d. AWARD DATE** (YYYYMMDD)	**4. REPORTING PERIOD** (YYYYMMDD)
61 Route 9W, Palisades, NY 10964	20100216	61 Route 9W, Palisades, NY 10964	20100216	a. FROM 20100101 b. TO 20110930

SECTION I - SUBJECT INVENTIONS

5. "SUBJECT INVENTIONS" REQUIRED TO BE REPORTED BY CONTRACTOR/SUBCONTRACTOR (If "None," so state)

NAME(S) OF INVENTOR(S) (Last, First, Middle Initial) a.	TITLE OF INVENTION(S) b.	DISCLOSURE NUMBER, PATENT APPLICATION SERIAL NUMBER OR PATENT NUMBER c.	ELECTION TO FILE PATENT APPLICATIONS (X) d. (1) UNITED STATES (a) YES	(1) UNITED STATES (b) NO	(2) FOREIGN (a) YES	(2) FOREIGN (b) NO	CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER (X) e. (a) YES	e. (b) NO
N/A								

f. EMPLOYER OF INVENTOR(S) NOT EMPLOYED BY CONTRACTOR/SUBCONTRACTOR

(1)	(2)
(a) NAME OF INVENTOR (Last, First, Middle Initial)	(a) NAME OF INVENTOR (Last, First, Middle Initial)
(b) NAME OF EMPLOYER	(b) NAME OF EMPLOYER
(c) ADDRESS OF EMPLOYER (Include ZIP Code) N/A	(c) ADDRESS OF EMPLOYER (Include ZIP Code)

g. ELECTED FOREIGN COUNTRIES IN WHICH A PATENT APPLICATION WILL BE FILED

(1) TITLE OF INVENTION	(2) FOREIGN COUNTRIES OF PATENT APPLICATION

SECTION II - SUBCONTRACTS *(Containing a "Patent Rights" clause)*

6. SUBCONTRACTS AWARDED BY CONTRACTOR/SUBCONTRACTOR (If "None," so state)

NAME OF SUBCONTRACTOR(S) a.	ADDRESS (Include ZIP Code) b.	SUBCONTRACT NUMBER(S) c.	FAR "PATENT RIGHTS" d. (1) CLAUSE NUMBER	d. (2) DATE (YYYYMM)	DESCRIPTION OF WORK TO BE PERFORMED UNDER SUBCONTRACT(S) e.	SUBCONTRACT DATES (YYYYMMDD) f. (1) AWARD	f. (2) ESTIMATED COMPLETION
N/A							

SECTION III - CERTIFICATION

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I certify that the reporting party has procedures for prompt identification and timely disclosure of "Subject Inventions," that such procedures have been followed and that all "Subject Inventions" have been reported.

a. NAME OF AUTHORIZED CONTRACTOR/SUBCONTRACTOR OFFICIAL (Last, First, Middle Initial)	b. TITLE	c. SIGNATURE	d. DATE SIGNED
Zappa, Christopher, J.	Senior Associate Research Professor	Christopher J. Zappa	12-9-11